# Preliminary Study of Diffuse Horizontal Illuminance in Hong Kong

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**Abstract**

According to the recent progress of the way of thinking on the visual environment and the change of the energy circumstances, many improved models have proposed for the estimation of the illumination level in interiors. The estimations based on these models proved that the sky illuminance vary in different locations and countries. In order to investigate daylight availability data in low latitude/tropic area which extremely lacking at the present stage, a measurement of daylight and solar radiation was done in Hong Kong. After the records of the data strictly inspected, the data of the diffuse illuminance has been rearranged into a classification based upon the sky conditions of the whole day specified by cloud ratios. Based upon the diffuse horizontal illuminance data gathered in Hong Kong during October 2006 to September 2007, a preliminary study on the values of the horizontal illuminance from the unobstructed sky by the statistical analysis can be proposed.

**Keywords:** horizontal illuminance, measurement data, sky conditions.

## 1. INTRODUCTION

The standard value of the horizontal illuminance from unobstructed sky is considered very essential and fundamental for the energy conservation in the field of lighting design in order to keep the minimum level of the illuminance in interiors. According to the recent progress of the way of thinking on the visual environment and the change of the energy circumstances, many improved models have proposed for the estimation on the illumination level in interiors. The estimations based on these models proved that the sky illuminances vary in different locations and countries.

Based upon the diffuse horizontal illuminance data gathered in Hong Kong during October 2006 to September 2007, a proposal on the values of the horizontal illuminance from the unobstructed sky can be made by the statistical analysis.

## SKY CONDITIONS SPECIFIED BY CLOUD RATIO

Two CIE standards, that is, the CIE Standard Clear Sky and the CIE Standard Overcast Sky already recommended as the standards of sky luminance distribution. Unfortunately, those skies only represent for two extreme sky conditions, that is, the completely clear sky and the heavily cloud sky. However, most of real sky conditions are not similar to them. They are between both extreme skies above stated, called “intermediate sky”. In analyzing the measured data of daylight and solar radiation, it is necessary to sort the data by sky conditions. They are divided conveniently in three sky conditions, such as the clear sky condition (including quasi-clear sky), the intermediate sky condition and the overcast sky condition (including quasi-overcast sky). However, it is not satisfactory to know the sky conditions of the whole day. For purpose, a parameter which can specify the real sky conditions is absolute necessary.

The ratio of the diffuse illuminance and/or irradiance to the global illuminance and/or irradiance is defined and named Cloud Ratio, which have been considered as the most practical and convenient parameter for this purpose.

### Definition of Cloud Ratio

The Cloud Ratio has originally defined as the proportion of the diffuse irradiance to the global irradiance and used for to the estimation of solar radiation, that is, for solution of heating and cooling problems in building which applied the ratio of the diffuse illuminance to the



In this study, the ratio on irradiance is called “Cloud Ratio on Irradiance (Ce)” and the ratio on illuminance is called “Cloud Ratio on Illuminance (Cv)”. Cloud ratio on irradiance can be calculated theoretically by the following equation :

$$Ce = Eed / (Eed + Ees) = Eed / Eeg \quad ...(1)$$

where : Eeg is global horizontal irradiance [W/m$^2$], Eed is diffuse horizontal irradiance [W/m$^2$], and Ees is direct solar horizontal irradiance [W/m$^2$].

Cloud ratio on illuminance (Cv) is defined in a similar way to cloud ratio on irradiance (Ce). Cloud ratio on illuminance can be calculated theoretically by the following equation:

$$Cv = Evd / (Evd + Evs) = Evd / Evg \quad ...(2)$$

where : Evg is global horizontal illuminance [Ix], Evd is diffuse horizontal illuminance [Ix], and Evs is direct solar horizontal illuminance [Ix].

## Typical Diurnal Fluctuation of Cloud Ratio

Theoretically, the values of both cloud ratios should be equal to 1.0 when the sky is completely overcast of the whole day. Both the cloud ratios on irradiance and illuminance of a clear day of the whole day seem to be dependent on the solar position. Their values were almost constant when the solar altitude was not so low and they increased as the solar altitude became low. The ratios of the overcast day of the whole day were almost equal to 1.0 throughout the whole day. The Examples of both the cloud ratios of an intermediate day of the whole day show the frequent and rapid change of their values throughout the whole day. Their values sometimes seemed to be almost equal to those of the clear condition and instantly move to those of the overcast conditions. Most values of cloud ratio on irradiance were a little smaller than those of cloud ratio on illuminance of the same time.

## Diffuse Horizontal Illuminance

Many equations have been proposed which show the relation between the horizontal illuminance from unobstructed sky (Ea) and the solar altitude ($\gamma s$). Nakamura et al. [7-8] have been proposed the equations of the horizontal illuminance from unobstructed the representative value, respectively. The equations are as follows :

$$Eu = 2.0 + 80.0 \sin^{0.8} \gamma s \quad ...(3)$$

$$Es = 0.5 + 42.5 \sin \gamma s \quad ...(4)$$

$$El = 15.0 \sin^{1.2} \gamma s \quad ...(5)$$

where : Eu and El are the upper limiting value and the lower limiting value of the horizontal illuminance from the unobstructed sky respectively and Es is the representative value of the horizontal illuminance from unobstructed sky.

Figure 1 shows the upper limiting value and the lower limiting value of the horizontal illuminance from the unobstructed sky respectively and Es is the representative value of the horizontal illuminance from unobstructed sky with various equations proposed, respectively.

Horizontal illuminance from unobstructed sky both clear sky and overcast sky also can be derived from the zenith luminance value and CIE Standard Clear Sky or CIE Standard Overcast sky.

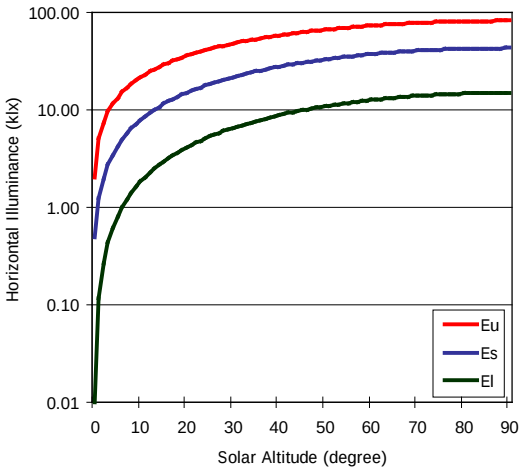


**Figure 1.** The upper limiting value and the lower limiting value of the horizontal illuminance from the unobstructed sky respectively and Es is the representative value of the horizontal illuminance from unobstructed sky.

Other equations of the horizontal illuminance from unobstructed sky have been proposed in relation to the sky conditions. The equations are as follows [8-13] :

| | | |
|---|---|---|
| - Krochmann | $Ea(cl) = (1.1 + 15.5 \sin^{0.5} \gamma s)$ | ...(6) |
| - Chroscicki | $Ea(cl) = \{3 + 0.17 (\gamma s/^{o})\}$ | ...(7) |
| - Krochmann | $Ea(oc) = (300+21000 \sin \gamma s)$ | ...(8) |
| - Kittler | $Ea(oc) = 9750 (1 + 3/2 \sin \gamma s) \sin \gamma s$ | ...(9) |
| - Feitsma | $Ea(oc) = 467 (\gamma s/^{o})$ | ...(10) |
| - Hopkinson | $Ea(oc) = 215 (\gamma s/^{o})$ | ...(11) |
| - R. Rahim | $Ecl = 3.0 + 17 \sin^{0.9} \gamma s$ | ...(12) |
| | $Ein = 1.1 + 48 \sin^{1.3} \gamma s$ | ...(13) |
| | $Eoc = 0.6 + 78 \sin^{1.8} \gamma s$ | ...(14) |

where : the Ecl, Ein, and Eoc are the horizontal illuminance from unobstructed sky for clear sky, intermediate sky and overcast sky, respectively, Ea is the representative value of the horizontal illuminance from unobstructed sky, and γs is the solar altitude.

Figure 2 shows the horizontal illuminance from unobstructed sky of the clear sky proposed by various researchers with the curves of the equations (3), (4) and (5), respectively.

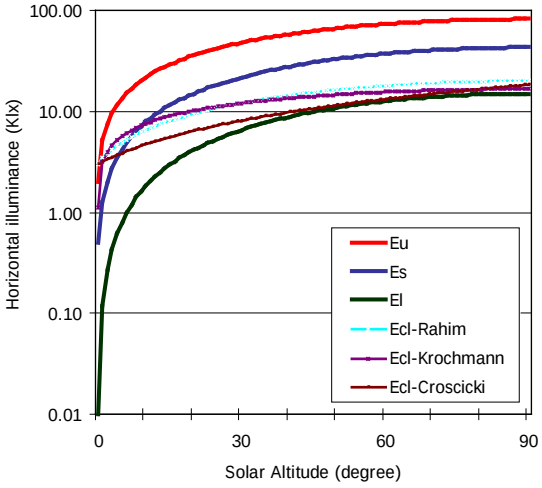


**Figure 2.** Horizontal illuminance from unobstructed sky of the clear sky proposed by various researchers with the curves of the equations (3), (4) and (5), respectively.

Figure 3 shows the horizontal illuminance from unobstructed sky of the intermediate sky proposed by various researchers with the curves of the equations (3), (4) and (5), respectively.

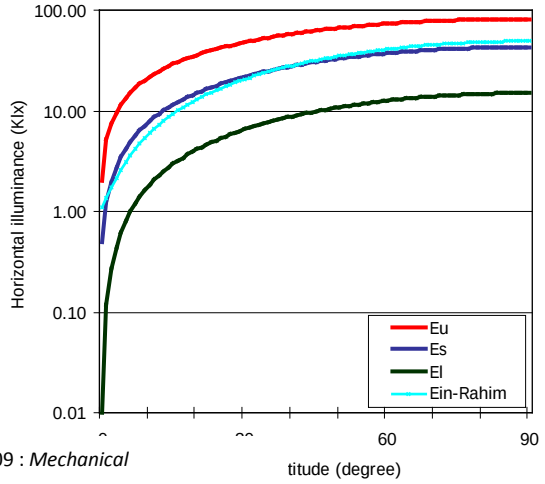




**Figure 4.**Horizontal illuminance from unobstructed sky of the intermediate sky proposed by various researchers with the curves of the equations (3), (4) and (5), respectively.

Figure 4 shows the horizontal illuminance from unobstructed sky of the overcast sky proposed by various researchers with the curves of the equations (3), (4) and (5), respectively.

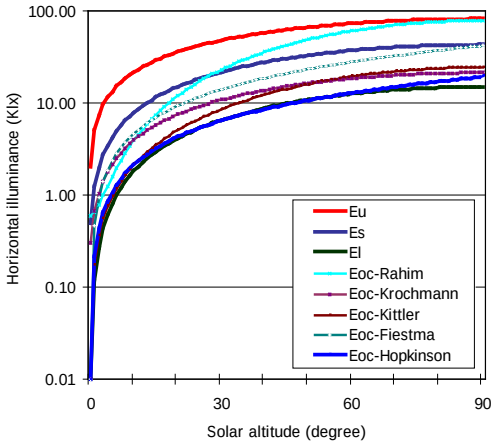


Figure 4
Horizontal illuminance from unobstructed sky of the overcast sky proposed by various researchers with the curves of the equations (3), (4) and (5), respectively.

## 2. RESULT AND DISCUSSION

### Classification of Data Based upon the Sky Conditions

The diurnal fluctuation of cloud ratio on irradiance has been mainly inspected and compare with the cloud ration on illuminance. The result shows the sky conditions specified by cloud ratios, the clear and overcast days were 15 and 104 days, respectively and the rest, 219 days had intermediate sky conditions (were: clear sky 4.44%, intermediate sky 64.47%, and overcast sky 31.09%, respectively).
The differences of the results are caused by the different period of calculation. Sky conditions specified by cloud ratios are daily between sunrise to sunset, and sky conditions calculated by sunshine duration are based on 8 hours daily working time.

After the records of the data were strictly inspected, the data of the diffuse horizontal illuminance has been rearranged into a classification based upon the sky conditions of the whole day conditions of the whole day specified by cloud ratios. The general tendencies, i.e. the effects of sky conditions to the horizontal illuminance from unobstructed sky have been roughly inquired, for example:

- Under the condition of the clear sky, the values of the horizontal illuminance from unobstructed sky are often smaller than those under the other conditions.
- The values for solar altitude from 0° until 45° are small and increased correspond to the solar altitude.
- The values of the horizontal illuminance from unobstructed sky does not change or reduces inversely, if the solar altitude becomes higher than about 45°.

Data of diffuse horizontal illuminance gathered from October 2006 to September 2007 have been processed by half-hourly intervals and 6-degree intervals. Further, all data were processed into 6-degree intervals and recalculated while based upon the sky conditions of whole day which have been specified by diurnal fluctuations of whole day which have been specified by diurnal fluctuation of cloud ratios.
After strict examination and careful analysis, the relationships between the horizontal illuminance from the unobstructed sky and solar altitude for these three skies conditions cloud be formulated. They were based upon the mean for each 6 of solar altitude and classified by three skies conditions. The proposed equations are as follows:

$$Ecl = 2.2 + 22 \sin^{0.9} \gamma s \quad ...(15)$$
$$Ein = 1.1 + 42 \sin^{1.3} \gamma s \quad ...(16)$$
$$Eoc = 0.6 + 50 \sin^{1.8} \gamma s \quad ...(17)$$

where : the Ecl, Ein, and Eoc are the horizontal illuminance from unobstructed sky for clear sky, intermediate sky and overcast sky, respectively, and γs is the solar altitude.

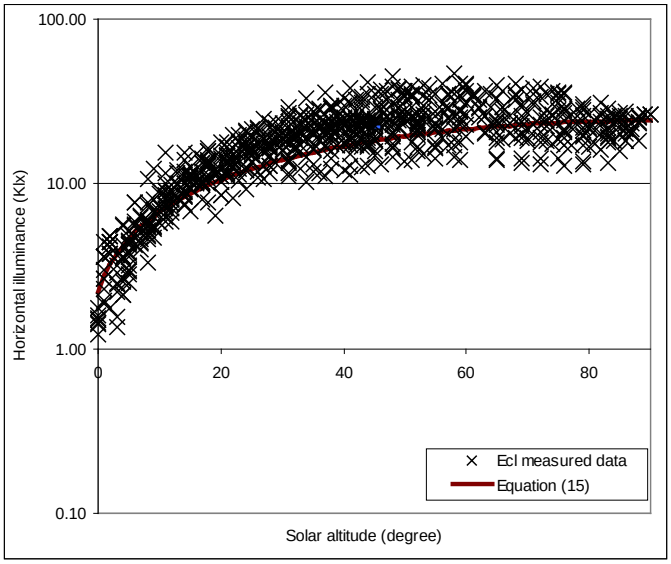


**Figure 5.** Data of horizontal illuminance from unobstructed sky of the clear sky proposed with the curve of the equations (15).

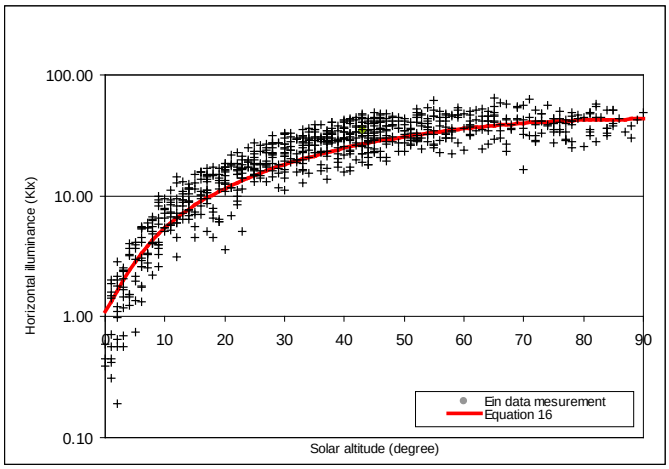


**Figure 6.** Data of horizontal illuminance from unobstructed sky of the intermediate sky proposed with the curve of the equations (16).

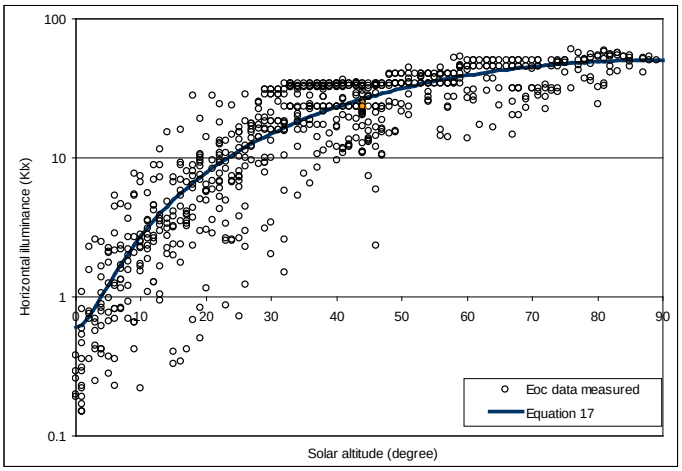


**Figure 7.** Data of horizontal illuminance from unobstructed sky of the overcast sky proposed with the curve of the equations (17).

## Representative value of the horizontal illuminance (Ea)

It has become necessary to fix conveniently a mean value as representative value corresponding to each solar altitude including the consideration about the distribution. Moreover, it has been desirable that the representative value has been widely applicable to a rather large territory.

The yearly relative Frequency of occurrence of the three skies in Hong Kong calculated from the relative sunshine duration and is assumed to be 3.69%, 66.67%, 29.64%, respectively [11]. Using this frequency of occurrence of the three skies, the representative value of the horizontal illuminance from unobstructed sky (Ea) could be represented as the sum of the products of each value of the horizontal illuminance of the three skies and their frequency of occurrence. The proposed equation is as follows :

$$Ea = [\ (0.369 \times Ecl) + (0.6667 \times Ein\ ) + (0.2964 \times Eoc)\ ] \qquad ...(18)$$

Figure 8 shows the value of horizontal illuminance from the unobstructed sky and the curve of the equation (18) with the upper and the lower limiting values by equations (3) and (5).

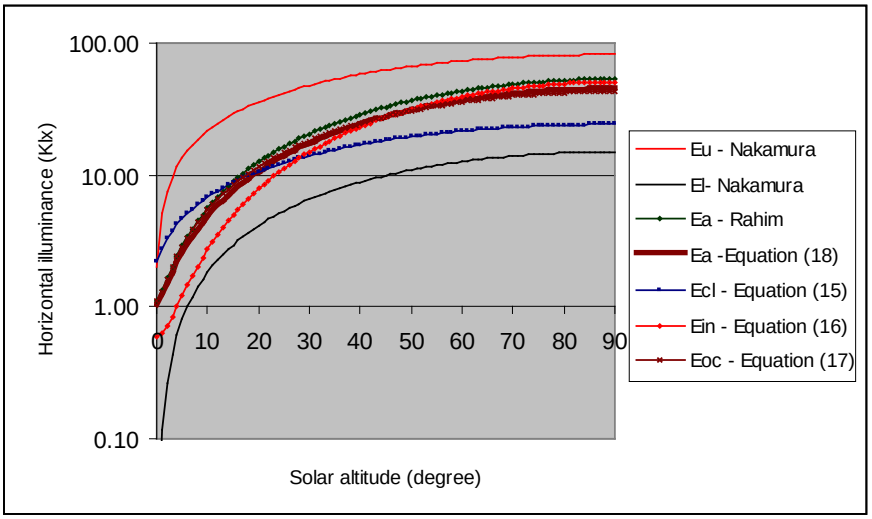


**Figure 8.** The value of horizontal illuminance from the unobstructed sky and the curve of the equation (18) with the upper and the lower limiting values by equations (3) and (5).

## Cumulative frequencies of the Horizontal Illuminance

The standard of the horizontal illumination from unobstructed sky has been inevitably constructed by the statistically treatment with the frequency of occurrence of the solar altitude throughout a year and the distribution of the values of the horizontal illumination from unobstructed sky of the three skies conditions.
The calculation of the percentage and the cumulative percentage of the hours corresponding to the each horizontal illuminance from unobstructed sky to the whole working hours have been performed by the following steps :

- The solar altitude to each representative value calculated by the equation (18).
- The frequency of occurrence of the hours to each solar altitude obtained as above to the whole working hours throughout a year has been calculated.
- The frequency occurrence calculated above distributed to each mean horizontal illuminance value.
- In order to get the percentage of the hours corresponding to each horizontal illuminance from unobstructed sky to the whole working hours duration, the frequency of occurrence distributed above has been integrated at each horizontal illuminance from unobstructed sky from the value 0 lx to that of 76.73 Klx.
- The cumulative percentage calculated from the percentage obtained as above.
- The value of the horizontal illuminance from unobstructed sky corresponding to each round cumulative percentage reversely calculated.

For comparison to other research works on the horizontal illuminance from unobstructed sky, Table 1 shows a review of measured skylight availability data [1-4, 7-12]. Table 2 shows the standard relation between the horizontal illuminance from unobstructed sky and its cumulative percentage of the hours, for which the illuminance level is available to the working hours.

**Table 1.** Review of measured skylight availability data

| Location | Representative Ea (Klx) | Reference |
|---|---|---|
| Darwin | 12.7 | Ruck, 1985 |
| Brisbane | 7.9 | Ruck, 1985 |
| Broken Hill | 5.9 | Ruck, 1985 |
| Sydney | 8.8 | Ruck, 1985 |
| Paris | 5.0 | Fournol, 1951 |
| Kew/Bracknell | 3.0 | Hunt, 1979 |
| Roorkee | 8.0 | Narashiman, 1970 |
| Nagoya, Japan | 13.5 | Nakamura, 1979 |
| Pretoria | 10.0 | Richards, 1959 |
| Cape Town | 7.5 | Richards, 1959 |
| San Fransisco | 5.0 | Navvab, 1984 |
| Bandung, Indonesia | 10.0 | Adhiwijogo, 1969 |
| Makassar, Indonesia | 14.35 | Rahim, 1994, 2004 |

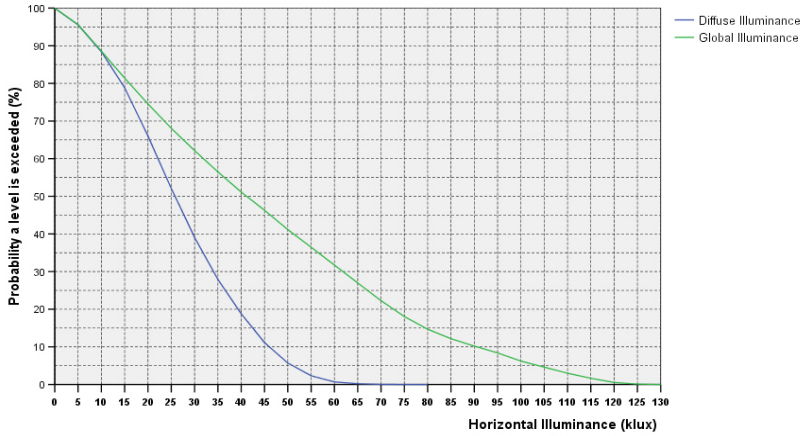


**Figure 9.** Relation between the horizontal illuminance from unobstructed sky and its cumulative percentage of the hours, for which the illuminance level is available to the working hours

**Table 2.** The percentage of illuminance level exceed in working time in Hong Kong (9 a.m. to 5 p.m.)

| Cumulative Percentage [%] | Horizontal Illuminance [klux] | Cumulative Percentage [%] | Horizontal Illuminance [klux] |
|---|---|---|---|
| 95 | 5.25 | 45 | 28.07 |
| 90 | 8.71 | 40 | 30.05 |
| **85** | **11.46** | 35 | 32.36 |
| 80 | 14.14 | 30 | 34.59 |
| 75 | 16.3 | 25 | 36.9 |
| 70 | 18.42 | 20 | 39.8 |
| 65 | 20.53 | 15 | 42.84 |
| 60 | 22.42 | 10 | 46.35 |
| 55 | 24.24 | 5 | 51.34 |
| | | 0 | 76.73 |



For about 85% of the time from 9am to 17pm in the year the outdoor diffuse horizontal illuminance will about 11.460 lux. This value can be used as a design sky for Hong Kong for calculating the absolute value of the illuminance inside the room using the Daylight Factor formula.

## The daylight factor approach to annual estimates

The daylight factor approach is invariably used to assess the potential of a design to provide useful levels of daylight illumination. The approach using CIE standard overcast sky, irrespective of the prevailing climatic conditions for the locale of the proposed design. And of course, the contribution of sunlight to internal illuminance is not modelled using this approach. Applying a simple technique, cumulative internal illuminance availability can be calculated from daylight factor values and charts of cumulative diffuse sky illuminance. This gives a first order approximation to annual daylighting provision from which supplementary lighting requirements can be estimated [14].

## Example

Suppose that the minimum required internal illuminance at a point in an office is 500 lux. This required the minimum Daylight Factor (DF) as follows:

$$DF = \frac{500x100}{11460} = 4.3\%$$

The minimum DF of 4.3 for this internal illuminance will be fulfilled for about 85% of the time in a year round.

## 3. CONCLUSION

One of the crucial problems in predetermining the role of daylighting in energy efficient buildings is the need for reliable local data on daylight availability. Daylight availability defined in terms of the external skylight illuminance available on an unobstructed horizontal plane for a certain percentage of daytime working hours or for specified periods (daily, monthly and yearly). Furthermore, one of the basic aims of collecting and measuring daylight and solar radiation levels in many locations on the globe is the mutual comparison and evaluation of available data gathered.

Based upon the diffuse horizontal illuminance data gathered in Hong Kong during October 2006 to September 2007, a proposal on the values of the horizontal illuminance from the unobstructed sky has been 11,46 Klx proposed. This proposal has been supposed to be proper that the value at Hong Kong should be extended as the standard value of the horizontal illuminance from unobstructed sky in Hong Kong.

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